Recent Advances in Cryogenic Optics Technology for Space Infrared Telescope and Interferometer Systems

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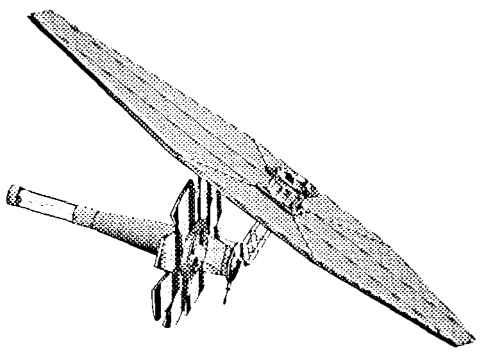
ABSTRACT

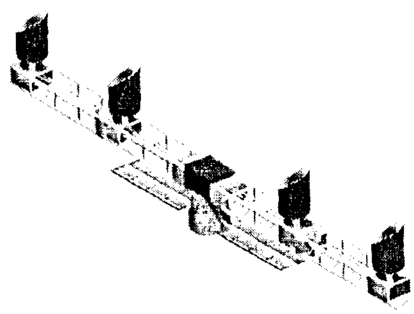
In this paper we will describe recent advances in the development of optical systems for future space infrared telescope and interferometer applications which will operate at very low or cryogenic temperatures (T≤77K) with emphasis on beryllium and silicon carbide optics. New material formulations and advanced processing and manufacturing techniques are enabling the development of large, very low mass, high performance cryogenic optics. The design, manufacturing and cryogenic testing of several recently developed mirrors and optical assemblies will be discussed.

1. INTRODUCTION

A number of future astrophysics and planetary science missions are currently being proposed and/or studied which will require the implementation of large Space based telescopes and interferometers. Some of these include the Space Infrared Telescope Facility (SIRTF), the Space Interferometry Mission (SIM), the Next Generation Space Telescope (NGST), the Terrestrial Planet Finder Array (TPFA) and the Terrestrial Planet Mapper Array (TPMA). Schematic representations of concepts for two of these missions, NGST and TPFA, are shown in Figure 1.



Next Generation Space Telescope[1]



Terrestrial Planet Finder Array[2]

Figure 1. Future Cryogenic Space Optical System Concepts

The NGST is currently envisioned to be a large deployable telescope with an ≈8m aperture, passively cooled to 30-70K and performing imaging and spectroscopic studies between 0.5μm and 20μm (diffraction limited at 1-2μm). The TPFA concept show in Figure 1, is a multi-baseline interferometer composed of four 1.5m aperture telescopes, passively cooled to 35K, observing in the 7-17μm band and capable of achieving sufficient starlight nulling to enable imaging of earth-like planets around distant stars.

NGST and TPFA, as well as many of the other mission studies, have highlighted the infrared (≈1-20μm) as the key spectral region for observing programs aimed at the study of the early universe., the observation of extra-solar terrestrial planets, and the characterization of atmospheres of extra-solar planets in a search for markers pointing to life. At these wavelengths, in order to not be limited by thermal emission from the observatory, it is necessary to cool the optics to cryogenic temperatures. The exact operational temperature depends on the longest observing wavelength but is typically in the 5-70K range. This requirement, to operate at very low temperature, has a major impact on the mission architectures. At the same time, there is a strong desire on the part of the international space agencies to reduce the cost of future missions which drives the mission architects to simplify designs, accelerate development, reduce development costs, reduce the mass of the flight system and utilize smaller launch vehicles. The combination of science goals, engineering considerations and programmatic limitations places some unique requirements on the optical system designs and materials.

2. PREVIOUS CRYOGENIC SPACE TELESCOPES

To date, there are two well known examples of major civilian cryogenic telescopes which have been developed, launched and have successfully performed scientific investigations in space. In 1983, NASA launched the Infrared Astronomical Satellite (IRAS). The 70kg, IRAS telescope (optics and structure) was manufactured from vacuum hot pressed beryllium and operated at ≈4K, cooled with liquid helium carried on-board in a large dewar. The telescope was a Richey-Chretien type, with a 57cm aperture and was diffraction limited at ≈20μm. Twelve years later, in 1995, ESA launched the Infrared Space Observatory (ISO) which is still in operation. The 50kg ISO telescope has an invar/aluminum structure and lightweighted fused silica mirrors and is also cooled to ≈4K with on-board liquid helium. It too is a Richey-Chretien design, with a 60cm aperture and achieves diffraction limited performance at ≈5μm, much better than IRAS. The IRAS and ISO telescopes are shown in Figure 2 A&B.

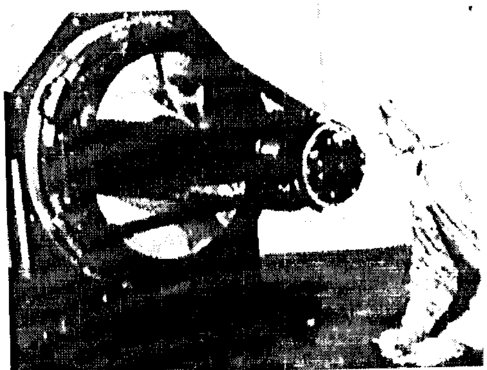


Figure 2A. The IRAS Telescope

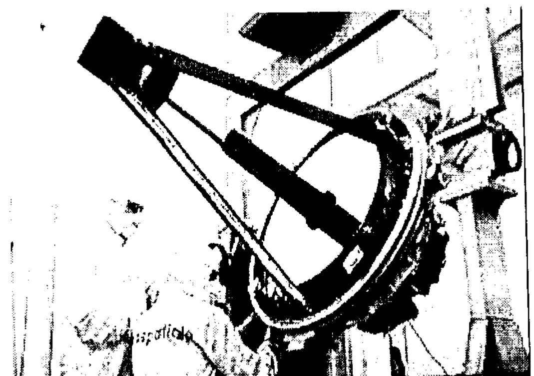


Figure 2B. The ISO Telescope

3. FUTURE CRYOGENIC SPACE OPTICAL SYSTEM DESIGN

IRAS and ISO have been very successful forerunners to future cryogenic space optical systems and have provided an invaluable base upon which the future systems can be built. However, as discussed above, a number of new and different factors will drive the development of the future cryogenic space telescopes and interferometers. Among other things, future systems will have to be larger, lower cost and lighter weight than their predecessors and most will be passively cooled as opposed to carrying large quantities of cryogen into space.

Key design considerations for these future systems will include cost, mass, manufacturability, complexity of the optics and structure, wavefront error, control methodology, thermal performance and athermalization, mode of cooling, launch survivability, on-orbit durability and system level testing. The design considerations and ultimate performance are directly linked to the materials that will be utilized to manufacture the optics and the structure. Candidate materials for cryogenic mirror manufacturing include fused silica, silicon carbide, beryllium, aluminum, composites (carbon fiber reinforced polymers, metal matrix and ceramic type), and various hybrids incorporating multiple materials. Candidates for precision cryogenic structures include aluminum, silicon carbide, beryllium, invar and composites, as well as hybrids. There is no perfect mate.rial or combinat ion of materials that are suit able for at l appl i cat ions. I 'ach candidate material has both positive and negative aspects with respect to cryogenic space optical system applications. The key to successful design of future. systems is to understand the. science goals of the particular mission, their implication in terms of engineering requirements, and the available cost and schedule to find the optimum set of materials to achieve the desired performance. A summary of selected material cons iderations for cryogenic optics is given in 'J 'able 1.

Fused Silica	Silicon Carbide	Beryllium	Aluminum	Composites (CFRP***)
PROS				
Large Experience Base Low Surface Scatter Good Figure Quality Good Dimensional Stability Low Specific Heat Good Homogeneity	• High Stiffness • Low Surface Scatter • Good Figure Quality • Good Dimensional Stability • Low Specific Heat • High Thermal Conductivity • Athermalized Systems • Near Net Shape with RB*	• Very Lightweight • High Stiffness • Good Figure Quality • High Thermal Conductivity • Easy to Mount • Athermalized Systems • Durable • Near Net Shape by HIP**	• Very Low Cost • Easy to Fabricate • High Thermal Conductivity • High Strength • Easy to Mount • Athermalized Systems • High Durability	• Low Cost • Very Low Mass • Tailorable Properties • High Stiffness • High Strength • Athermalized Systems • High Durability • Replication
CONS				
Low Thermal Conductivity Difficult to Mount Difficult to Athermalize Heavy111.... Fragile if Lightweighted	• Immature Technology • Limited Availability • Brittle • Difficult to Mount • Heavy • Extent of Possible Light-weighting Unknown	• Low Microyield • High Thermal Contraction • Null Figuring Required • Limited Availability • Limited Size • Surface Scattering • Expensive	• Very High Thermal Contraction • Heavy • Low Stiffness	• Poor Figure Quality • High Surface Scatter • Material Variability • Anisotropic • Moisture Absorbing • Outgassing
	* Reaction Bonded	**Hot Isostatic Pressed		*** Carbon Fiber Reinforced Polymer

able 1. Selected Mirror Materials Considerations for Cryogenic Space Optical Systems

4. CRYOGENIC OPTICS TECHNOLOGY DEVELOPMENT FOR SIRTF

The next major cryogenic space optical system to be developed by NASA is planned to be SIRTF, an 85cm clear aperture telescope, cooled to <5K and performing imaging and spectroscopy in the. 3.5μm to ≈160μm region of the spectrum. An artist's conception of SIRTF, currently scheduled to launch in 2002, is shown in Figure 3.

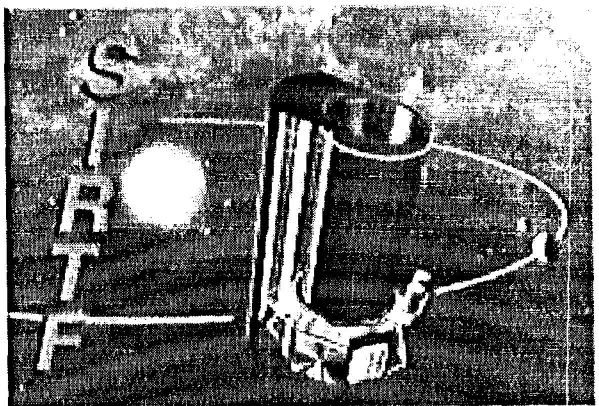


Figure 3. The Space Infrared Telescope Facility

In carly 1993, in preparation for S11<'1'1', the Jet Propulsion Laboratory (.1 1'1 .) embarked on a technology development program to demonstrate the viability of a lightweight, cryogenic telescope which had twice. the collecting area of IRAS, half the mass and was diffraction limited at a substantially shorter wavelength (6.5μm vs. 20pm). The initial effort focused on the manufacturing and cryogenic testing of two subscale (0.5m diameter) test mirrors fabricated from the two leading candidate mirror materials - beryl 1 ium and silicon carbide. This was followed by development and testing of a full scale (85cm clear aperture), lightweight IR telescope called the 1 nfrared Telescope '1 'echnology '1 'estbed (I'l''J''I'). Hughes Danbury Optical Systems (11 I)OS) was selected, via a competitive proposal process, to develop the 1'1''1"1' based on an a beryllium design.

4.1 Beryllium and Silicon Carbide..'cslsl Mirror Development

'1 'he 0.5m diameter beryllium test mirror was fabricated from a blank manufactured from Special] y processed 1-701 I powder at Brush-Wellman, inc. using the 1111' (hot isostatic pressing) proms. The special processing of the beryllium powder was aimed at achieving a very homogeneous starting material for the blank. It involved additional steps (beyond the standard 1-7[)11 specification) designed to remove impurities and care.fully control the particle size distribution. Following manufacture of the blank, precision machining, but no lightweighting, was done by Loral American] 3eryllium and optical finishing, to a spherical surface, was performed by Tinsley Laboratories, inc. A key element in the manufacturing plan was repeated acid etching and thermal cycling of the mirror, following each major processing step, to relieve any built up internal stress. The finished optic, shown in 1 'igure -4, had a 2m radius of curvature, a room temperature rms wavefront error of 0.072λ (λ= 633nm) and an rms surface roughness of 13Å.

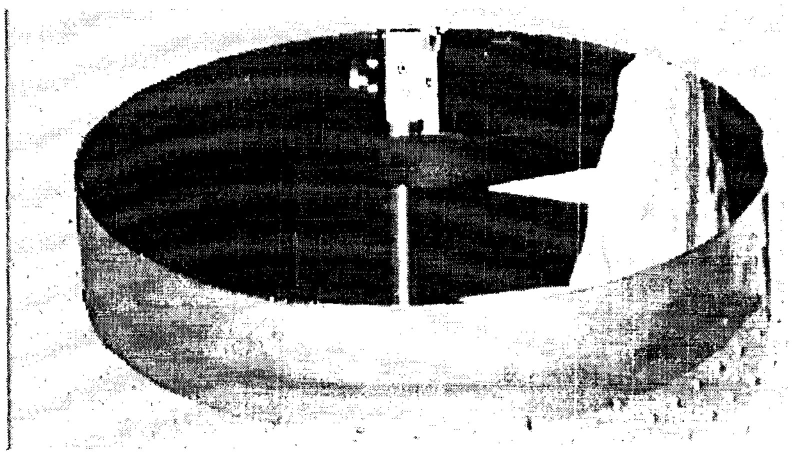


Figure 4. 50cm diameter beryllium test mirror

Cryogenic optical testing at 77K and 4.4K was performed using optical interferometry at the NASA Ames Research Center in the.ir Optical Test Facility which has been described previously.[3] The mirror proved to be the most stable large beryllium mirror ever measured.[4] The rms wavefront error at 77K was found to be O. 150λ. Further cooling to liquid helium temperature produced essentially no change and yielded **a** measured rms error of' O. 140λ at 4,4 K, The thermal distortion from mom temperature to 4 .4K of <().1 λ was comparable to that observed in most large fused silica mirrors. Even more importantly, there was no indication of measurable hysteresis in the. figure of the mirror as a result of thermal cycling, a problem which was well known in previous large troy] Ii um mirrors.[5]

The detailed causes of the observed hysteresis in previous beryllium mirrors has never been fully investigated. It is believed to be related to poor quality beryllium powder, poor consolidation prior to the HIP process and internal stresses built up in the optic during machining, grinding and polishing[6]. The manufacturing plan for the 50cm beryllium test mirror addressed all of these concerns. Ultimately, the combination of very clean beryllium powder with a uniform particle size distribution, care in the consolidation process and extensive stress relieving during machining, grinding and polishing, resulted in an excellent optic. Ultimately, the plan was to return the mirror to Loral American Beryllium for further machining and lightweighting followed by another round of cryogenic optical tests, however, this work has never been completed.

The 0.5m diameter silicon carbide test mirror was a closed back, lightweighted structure fabricated from reaction bonded optical (RBO) grade silicon carbide and rough ground to a sphere by United Technologies Optical Systems (UTOS). UTOS is no longer supporting this technology. However, Xinetics, inc. in Littleton, MA, USA is a current supplier. Litton Itek Optical Systems (since acquired by HDOS in Danbury, CT, USA) was responsible for the optical fabrication and polishing. The mirror, shown in Figure **5**, had **a** 2m radius of curvature and an rms wavefront error of 0.053λ (λ=633nm) at room temperature. Surface microroughness was never measured on this particular optic. However, surfaces of 30Å-40Å rms are achievable on RBO silicon carbide optics.[7]

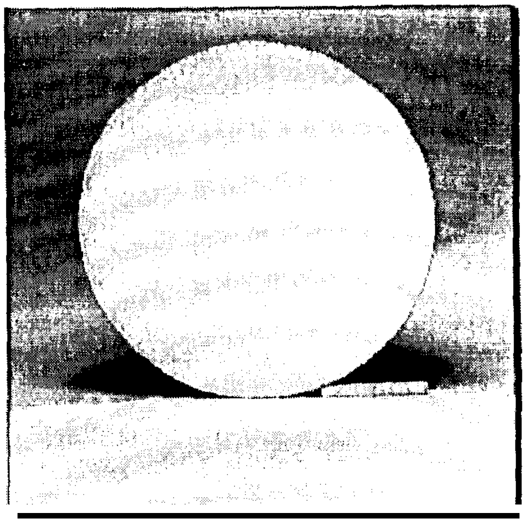
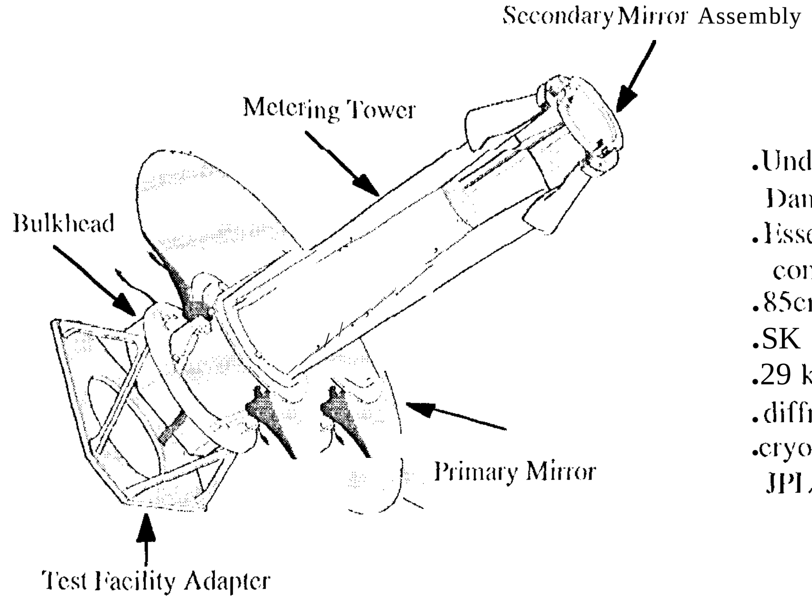


Figure 5. 50cm diameter RBO silicon carbide test mirror.

Cryogenic optical testing of the silicon carbide mirror was performed at Lockheed-Martin again using optical interferometry[8]. When cooled to 8K, the mirror showed an rms wavefront error of 0.126λ. Upon return to room temperature, a slight hysteresis of ≈0.03λ was noted. A second cycle, produced similar results. Lockheed believes that some of the error, and possibly some of the observed hysteresis was due to thermal effects on the test chamber window during the test which were difficult to control or quantify. There were plans to take the mirror to the Ames facility for further tests. However, when UTOS stopped producing the RBO silicon carbide optics, and this specific product was no longer available, those plans were dropped. The conclusion was that the silicon carbide mirror performance was comparable to that of the beryllium mirror and that on the basis of the subscale mirror evaluation program, both materials remained viable candidates for cryogenic optical system applications.

4.2 The Infrared Telescope Technology Testbed Design

In June of 1994, JPL issued the Infrared Telescope Technology Testbed RFP inviting industry and academia to propose to design and build a prototype telescope meeting the needs of the SIRTF mission. The principal requirements levied on the proposers were that the ITTT should achieve diffraction limited performance at 6.5μm, at 5.5K with an 85cm clear aperture and a total mass of <50kg. The primary mirror and system focal ratios were specified as F/1.2 and F/12 respectively. HDOS was selected to build the ITTT based on their concept for a (nearly) all beryllium telescope. A schematic representation of the HDOS ITTT design is shown in Figure 6. The telescope is fabricated from hot isostatic pressed I-70H (special) beryllium identical to that used in the test mirror except for six titanium biped flexures and several pins used to mount the primary and secondary mirrors. The design is based on a single arch primary mirror attached to a lightweight bulkhead via three of the flexures. The secondary mirror is mounted in a similar fashion to the secondary mirror assembly. The secondary mirror assembly is attached to a lightweight metering tower which incorporates the primary and secondary cone baffles and three longitudinal struts into a single machined piece. Copper cooling straps are used to facilitate cooling of the ITTT in the test chamber. The secondary mirror assembly is designed to accommodate a one degree of freedom focus mechanism but this element has not been incorporated into the current hardware. The total mass of the ITTT at completion is estimated to be 29kg.



- Under development at Hughes Danbury Optical Systems
- Essentially all beryllium construction
- 85cm clear aperture
- 5K operation
- 29 kg mass
- diffraction limited at 6.5μm
- cryogenic optical testing at JPL

Figure 6. The Infrared Telescope Technology Testbed

4.3 The SIRTF Telescope Test Facility

The Ames facility is too small to accommodate the ITTT for cryogenic testing. Consequently, while HDOS was manufacturing the ITTT, JPL developed the SIRTF Telescope Test facility (STTF) shown in Figure 7. Briefly, the STTF which has been described in detail elsewhere [9,10] consists of three concentric shells. The outer shell maintains the vacuum, the intermediate shell is at liquid nitrogen temperature cooled by a single tank at the base, and the inner shell is at liquid helium temperature cooled by dual tanks at the top and bottom. These tanks also supplies cryogen for cooling a vibration

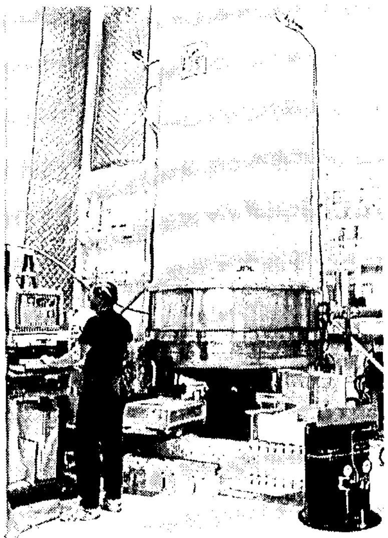


Figure 7. The SIRTF Telescope Test Facility

Figure 8. The Infrared Telescope Technology Testbed Primary Mirror Assembly

isolated precision gimbal mount and the experimental hardware which can be mounted either on the upper or lower tank. The upper tank is movable within the helium shroud thus accommodating optics of differing focal ratio. Each of the tanks has a cylindrical hole through its center to allow light to pass. The interior diameter of the helium shroud is 1.4m. in the testing of the ITTT Primary Mirror Assembly (PMA) which is described in detail in section 4.4, the hardware was mounted to the. gimbal via thee titanium flexures and the. gimbal/PMA assembly was attached to the base of the upper tank with the mirror facing down. Copper straps to the tank baseplate provided cooling and platinum resistance thermometers provided a means to monitor temperature. Near the base, are two shutters, an inner one at helium temperature and outer one at nitrogen temperature. These are normally closed and can be easily and quickly opened prior to measurement. The base of the vacuum shell has an optical window, below which is an instrument rack upon which rests a turning mirror, a null lens and a Zygo GPI phase shifting visible (633nm) interferometer. The entire assembly, tank and instrument rack is mounted on a large aluminum triangular frame which rests on three Newport Research pneumatic vibration isolation legs.

4.4 Testing of the Infrared Telescope Technology Testbed

HDOS fabricated the PMA, which includes the primary mirror, the bulkhead, the metering tower adapter tube, the primary mirror biped flexures and the cooling straps and the test facility adapter, and delivered it to JPL in July, 1995. A photograph of the PMA is shown in Figure 8. The initial room temperature measurements on the PMA showed an rms surface error of 0.192λ (λ= 633nm) with a peak-to-valley error of 1.56λ. The dominant error feature was a series of concentric zones which resulted from form grinding in the early stages of optical fabrication. The zones were 1-2 waves in height and have subsequently been removed with further small tool computer controlled polishing at HDOS. As mentioned previously, large beryllium optics have traditionally shown "thermal hysteresis", that is, they changed shape following cycling between room temperature and cryogenic temperature. The PMA was cycled five times to 77K and three times to 8K with no evidence of hysteresis. Room temperature data recorded following these multiple cycles showed an rms surface error was 0.194λ and the peak-to-valley error was 1.35λ. The slight change in the measured peak to valley error is not believed to be significant.

While the I'MA showed no hysteresis, it did show a moderate cryogenic distortion. At **77K,** the rms surface error was found to be 0.580λ and the peak-to-willcy error was **4** .42λ. At SK, the rms surface error was 0.588λ and the peak-to-valley error **was 4** .30λ. It is our conclusion that there is essentially no difference between the liquid nitrogen and liquid helium test data. Furthermore, the data was highl y repeatable from Cycle to Cycle.

Following the discovery of the cryogenic distortion in the I'MA, an investigation to determine its source ensued. First, the possibility of systematic errors in the test set-up was investigated. The Ph4A was rotated 120° and cryo-tested again. The cryo-distortion rotated with the hardware. Then, the null lens was rotated 180° with no effect. Secondly, the I'MA was decoupled from the aluminum adapter plate and the. aluminum biped flexures and cryo-tested suspended from a simple three point kinematic mount. Again, no change was observed. Following that, the primary mirror was removed from the I'M A and itself cryo-tested using the same mounting scheme. The observed error in the primary mirror matched the error measured in the PMA thus indicating that the source of the cryo-distortion was in the mirror itself and not in the mounting hardware. Finall y, the entire I'MA was reassembled and measured once again at liquid helium temperature. The results were essent i all y identical to those measured earlier.

The proposed solution to the cryogenic distortion problem was to "null- figure" the mirror. This is a process which had been demonstrated experimentally in fused silica [11] and involves refiguring of the optic at room temperature incorporating the negative of the cryogenic distortion observed at the desired operational temperature such that when cooled, the correct figure is achieved. 'Ibis is only possible if there is no thermal hysteresis in the mirror and bad never been demonstrated on a beryllium optic. The PMA was shipped back to 11110S in February, 1996. The concentric zones were removed and the mirror was null figured in such a manner so as to have the correct shape at SK. This process was accomplished with computer controlled polishing using small tools. The PMA was returned to J]']. in September, 1 996. Preliminary testing to 77K indicates that the refiguring process has been successful and that null figuring has been demonstrated on a beryllium mirror for the first t i me. The measured rms surface error at 77 K was 0.165λ and the peak-to-valley error was 1.38λ. Further testing to <SK will be performed, but no significant changes arc anticipated.

4.S Silicon Carbide Cryogenic Optical Test Flat for the STTF

The remaining pieces of the 1'1"1 'T telescope assembl y are in the final stage of manufacturing and will be delivered to JPL soon. Following the current PMA tests, the telescope will be assembled, aligned and tested in the S'1"1'1'. The plan is to test the 1'1"1'1' in the autocollimation mode utilizing a large cryogenic optical test flat (COTF). in late 1994, J]'], received proposals from industry and academia to produce this optic. The principal requirement was that the COTF be 90cm in diameter and maintain an rms surface flatness of ≤0.07μm at SK The leading candidate. materials were fused silica and silicon carbide.

Several key issues were considered in making the choice of material for the COTF. First, it is much easier to cool silicon carbide than fused silica due to the much higher thermal conductivity of the former. For that reason, silicon carbide seemed to be an attractive choice. However, clearly, the maturity of the fused silica technology was and still is far greater than that of silicon carbide. The tests on the 50cm RBO silicon carbide test mirror were encouraging as well as some similar data on cryogenic t est ing of a 25cm diameter chemical vapor deposit ed silicon carbide mirror[12]. Furthermore, Lockheed-Martin had established a collaboration with the Vavilov State Optics Institute in St. Pet ersburg, Russia and produced a series of sil icon carbide mirrors based on a process similar to the UTOS process. Two mall mirrors including a 17cm diameter sphere and a 31 cm x 21 cm flat were optical] y tested at 6K and showed good performance[13]. In **addition,** a lightweighted 60cm diameter mi rror was produced , though not for cryogenic applications[14]. The lightweighted mirror weighs ≈5kg, shows a room temperature rms wavefront error of 0.024λ (λ=633nm) and has a surface roughness of 10-20Å. A phot ograph of the back side of this mirror is shown in Figure 9.

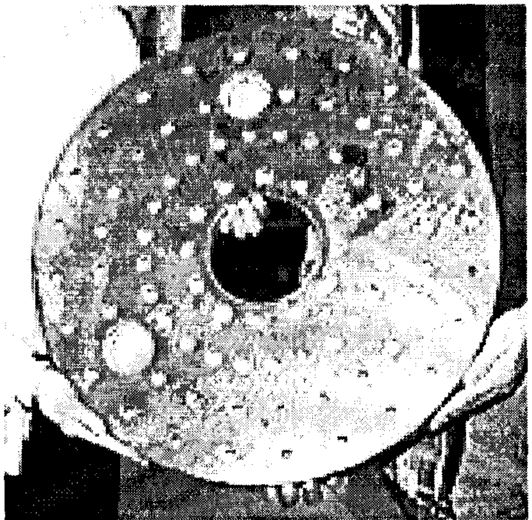


Figure 9. 60cm Diameter Russian Silicon Carbide Mirror

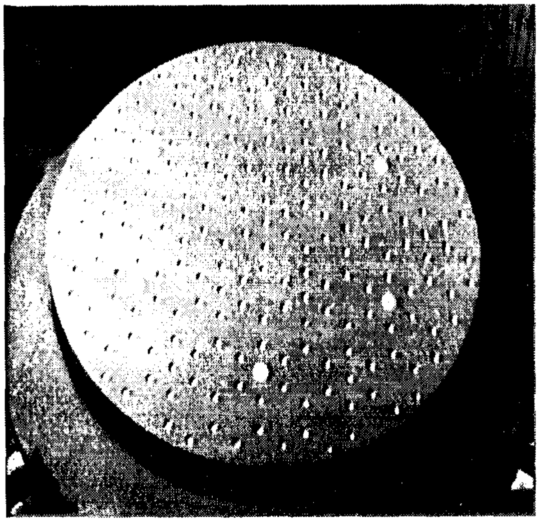


Figure 10. 90cm Diameter Cryogenic optical Test Flat for the S'1"1'1'

With this information in hand, Lockheed-Martin in collaboration with the Vavilov State Optics Institute in St. Petersburg, Russia was selected to produce the COTF. The optic and its six point aluminum mount have been fabricated in Russia and wil l b c delivered to J]']. shortl y for integration into the STTF . Init ial room temperat ure tests performed in St. Petersburg show an rms surface error of 0.07λ (λ= 633nm) and a peak to Valley error of 0.4 λ for the COTF. Cryogenic opt ical test ing, also performed in St. Petersburg, has indicated that the rms wavefront error at 4K is ≈0.085λ with a peak to val]cy error of O.4 λ, thus meet ing the stated requirement. A picture of the back side of the COTF blink is shown in Figure 10.

4.6 Future SIRTF Telescope Technology

When the COTF arrives at J]']., it will bc mounted on the STTF gimbal and at tached to t he upper hel ium tank. Once the 1'1"1"1' metering t ower is completed and delivered to JPL it will bc integrated with the PMA and the secondary mirror assembly and the telescope wi ll bc al igned. '1 'hc full y integrated ITT will then bc mounted on the lower helium tank in the STTF facing up and autocollimation test ing will bc performed usi ng the COTF to verify performance at 5 K. If the performance is adequate and meets the prescribed error budget, the ITT will bc removed from the STTF and vibrat ion tested to the levels appropriate for the Delta class launch vehicles. Following vibration tests, the hardware will bc rc-tested in the S"1''1'1 to verify alignment and cryogenic optical performance following simulated launch loads.

Several possible uses are being considered for the 1'1"1"1' following technology validation. There is a possibilit y that some elements of the hardware could be ut ilized in the S11<'1'1: flight telescope. The primary mirror, for example, could bc refigured for the current SIRTF design. A second possibility is to utilize the ITT as a ground test article to validate performance of SIRTF instrument test modules or as a stimulus for the S1l<'l'I' end-to-end system tests. Finally, there is the possibility that the telescope could be utilized as part of a future mission.

s. CONCLUSIONS

in the near fut ure, there is the possibility y that a number of large cryogenic optical s ystems wi ll be developed and launched int o space to perform a variet y of scient ific investigat ions. '1'here is currently a significant level of activity to develop the specialty opt ics requi red for such appl ications. A number of approaches are available to support these applications and the choice of materials and designs depends of the mission requirements. Considerable progress has been made recently in the development of large, lightweight beryllium and silicon carbide optics. 1 n particular, the "thermal hysteresis" problem in large cryogenic beryllium mirrors has been solved. Also, the process of "null figuring" has been demonstrated in beryllium. The state of the art in silicon carbide optics i s advancing rapidly and good performance at cryogenic temperature has been demonstrated in several mirrors. The future cryogenic optics needs of the space telescope and interferometry community appear to be reasonable extensions of existing technology if there is sufficient and continuing support for technology development.

6. ACKNOWLED GMENTS

Some of **the** work reported in this paper was performed for N ASA by the Jet Propulsion Laboratory, California Institute of Technology. Funding for this work was provided by the NASA Spacecraft Systems Division of the Office of Space Access and Technology (Code XS) as part of the Telescope Technology Program.

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